

Flare Production of ${}^6\text{Li}$ in Population II Stars

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ABSTRACT

Motivated by the recent report of a ${}^6\text{Li}$ detection in the atmosphere of HD 84937, we couple stellar evolution calculations with light isotope production via stellar flares. We find that as a consequence of their small convective envelope mass near the turn-off point, low-metallicity dwarfs and subgiants may possess observable amounts of ${}^6\text{Li}$ arising from such flare activity. We point out an observational test which could discriminate between flare produced ${}^6\text{Li}$ and protostellar ${}^6\text{Li}$. In the T_{eff} range 6000 – 6600 K, the ${}^7\text{Li}/{}^6\text{Li}$ ratio on the subgiant branch should increase as a function of T_{eff} if flare production is important, whereas the same ratio should be constant if a protostellar origin is the source of the observed lithium. The absence of a flare produced variation in the ${}^7\text{Li}/{}^6\text{Li}$ ratio would allow for a more reliable inference of the – cosmologically important – atmospheric depletion mechanisms in stars.

1. INTRODUCTION

The recent report of a detection of ${}^6\text{Li}$ in the metal poor halo star HD 84937 by Smith, Lambert, and Nissen (1993; hereafter SLN) could potentially be significant for cosmology, by constraining estimates for the primordial abundance of the heavier isotope, ${}^7\text{Li}$. Knowledge of the primordial ${}^7\text{Li}$ abundance, Li_p , constrains models of big bang nucleosynthesis (BBN). In particular, Li_p plays an important role in testing the validity of standard BBN (eg. Krauss and Romanelli 1990; Walker *et al.* 1991; Smith, Kawano and Malaney 1993). Li_p can potentially be derived from the Li abundances observed in the old halo dwarfs, which exhibit a plateau of nearly constant Li abundance for stars with $6400 \geq T_{\text{eff}} \geq 5600$ K, and depleted Li abundances relative to the plateau for both cooler dwarfs and cooler subgiants. The level of the plateau has often been associated with Li_p , consistent with standard BBN.

However, both Li isotopes are very fragile, ${}^6\text{Li}$ more so, and are destroyed easily by (p,α) reactions at only a few million degrees. Thus, already when stars arrive on the ZAMS, Li survives only in the outermost few percent (by mass) of the stellar interior. There are several physical mechanisms that indeed could alter the surface abundances during the stellar lifetime. Therefore, by necessity, a thorough understanding of these mechanisms must precede confident evaluation of Li_p . At present, at least two classes of stellar models are able to reproduce at least some aspects of the observations, but with different conclusions. Standard stellar evolutionary models (that ignore possible effects due to diffusion, rotational mixing, mass loss, magnetic fields) reproduce the general features of the observations with very little ${}^7\text{Li}$ depletion in the plateau (Deliyannis, Demarque, and Kawaler 1990). This implies self-consistency in standard BBN, and possibly the necessity for non-baryonic dark matter in galactic halos and larger scales. The reported detection of ${}^6\text{Li}$, at the level of about 1 part in 20 relative to ${}^7\text{Li}$, could then be consistent with its production by Galactic Cosmic Rays (GCR) in the interstellar medium. (GCR production of light isotopes in the early galaxy has been widely discussed in the recent literature; eg. Steigman and Walker 1992; Duncan, Lambert and Lemke 1992; Prantzos, Casse and Vangionni-Flam 1993; Malaney and Butler 1993; Feltzing and Gustafsson 1994; Fields, Olive, and Schramm 1994). However, the predictions of standard stellar models are blatantly contradicted by Pop I data (e.g. the Boesgaard Li gap and depletion of Be in F stars, the degree and timing of Li depletion in open clusters, the dispersion of Li abundances observed in open clusters, the higher Li abundances seen in short period tidally locked binaries), so the approximate agreement with the Pop II data could be coincidental.

On the other hand, stellar evolutionary models with rotationally induced mixing deplete the Li plateau by at least a factor of 3 - 10 (Pinsonneault, Deliyannis, and Demarque 1992), and the resulting Li_p introduces complications, and the possibility of some non-standard BBN (see Malaney and Mathews 1993 for review). If the $\text{D}+{}^3\text{He}$ constraint were relaxed, however (as also possibly suggested by rotational mixing, Deliyannis *et al.* 1994), consistent with the recent possible detection of D at high redshift (Songaila *et al.* 1994; Carswell *et al.* 1994), then standard BBN consistency could be maintained at low baryon density, requiring non-baryonic dark matter in galactic halos and larger scales. Consistency could again be maintained if the primordial helium abundance were just slightly higher than current estimates (and ignoring the quasar D), in which case dark galactic halos and larger scales could be baryonic.

Which class of stellar models, if either, might be more realistic? Newer models with improved internal physics have verified the robustness of the predictions in both standard and rotational models (Chaboyer and Demarque 1994). Unlike standard models, the rotational models can explain all the features of Pop I stars listed above. As in the case of Pop I stars, the rotational models predict a dispersion in the Li abundances in halo stars. A detailed analysis of the available data showed that such a dispersion indeed exists (Deliyannis, Pinsonneault, and Duncan 1993), and with about the right magnitude. Thorburn (1994) has verified this dispersion with a much larger sample of stars, though she suggested it might be related to Galactic Li enrichment combined with an age spread in the halo. Debate continues while the value of Li_p remains poorly known. Note that the curious linear relationship of Be/B *v* metallicity for the halo dwarfs (eg. Gilmore *et al.* 1992; Boesgaard and King 1993) might also warrant production scenarios for the light elements (${}^6\text{Li}$, ${}^7\text{Li}$, ${}^9\text{Be}$, ${}^{10}\text{B}$, ${}^{11}\text{B}$) other than

standard BBN+GCR. Also note that in standard BBN, ${}^6\text{Li}$ is at least 100 times less abundant than ${}^7\text{Li}$, and thus currently not possible to detect reliably even if perfectly preserved in the stellar atmosphere; however, other models of primordial nucleosynthesis predict much lower ratios of ${}^7\text{Li}/{}^6\text{Li}$ (e.g. Dimopoulos *et al.* 1988).

${}^6\text{Li}$ could provide clues in the following manner: Assuming the presence of ${}^6\text{Li}$ in a halo star, and if that ${}^6\text{Li}$ was indeed present in the material that formed the star, then the degree of rotationally induced depletion of ${}^7\text{Li}$ might be usefully constrained observationally. However, before drawing such powerful conclusions we should caution that – as pointed out by SLN – contamination of the atmosphere of HD 84937 with nucleosynthesis products arising from stellar flares is a real possibility. The introduction of a sufficient amount of flare produced ${}^6\text{Li}$ would place no constraints no rotational depletion of ${}^7\text{Li}$.

It is the purpose of this work, to quantitatively investigate the hypothesis that the ${}^6\text{Li}$ detected in HD 84937 was produced by stellar flares. We also provide predictions to distinguish between flare production and GCR production.

2. HD 84937; STELLAR MODELS

Any ${}^6\text{Li}$ that might be produced by autogenetic surface spallation (hereafter “surface spallated ${}^6\text{Li}$ ”) will be diluted in the surface convection zone (SCZ). Therefore, determining whether flares can produce observable amounts of ${}^6\text{Li}$ first requires estimating the size, in terms of mass, of the SCZ. Stellar evolutionary models show that the mass, M_c , of the SCZ depends on several model parameters: effective temperature, metallicity, choice of mixing length; it also depends on age (Deliyannis *et al.* 1990). Furthermore, given the fragility of ${}^6\text{Li}$ wrt (p, α) reactions, the base of the SCZ could be sufficiently hot and dense to destroy this ${}^6\text{Li}$. Indeed, detailed stellar models (Deliyannis *et al.* 1989, 1990) show that, if halo dwarfs formed with ${}^6\text{Li}$ (hereafter “protostellar ${}^6\text{Li}$ ”), this ${}^6\text{Li}$ could be preserved today only in stars near the turnoff. In this section we use standard (e.g. no diffusion, rotation, mass loss, or other additional physics not usually included in models) stellar evolutionary models to examine the necessary constraints (such as minimum M_c) on modelling of surface spallation that must be met if flares are to have produced ${}^6\text{Li}$ that is observable today in stellar atmospheres. (Possible complications due to dependence on parameters and additional physics is discussed in section 4.) We relate these findings to the case of HD 84937.

It should be kept in mind that the precise evolutionary status of HD 84937 is not known (SLN). For clarity, we define the turnoff as precisely the bluest point in a cluster; furthermore, stars above that point but still below the giant branch will be referred to as subgiants, whereas stars below that point will be referred to as dwarfs. When the B- V color of HD 84937 (~ 0.40 ; values in SIMBAD range from 0.37 to 0.42) is compared to the turnoff region of M92, which has similar metallicity and is one of the oldest and most metal-poor globular clusters, one finds that HD 84937 could either be a genuine dwarf just below the turnoff (position A in Figure 1), or a subgiant just above the turnoff (position B). It could even be (e.g. if it is older than M92) right at the turnoff. Note that Demarque, Deliyannis, and Sarajedini (1991) have derived an age of ~ 17 Gyr for M92 (Figure 1; slight differences between the models described below and of Demarque *et al.* do not affect the derived age); others have obtained similar ages (Chaboyer *et al.* 1992, Proffitt and Vandenberg 1991, slightly higher in Straniero and Chieffi 1991).

We begin in this section by considering the (standard) models of Deliyannis (1990) and Deliyannis *et al.* (1989, 1990), collectively referred to as DDK, for $Z = 10^{-4}$ ($[\text{Fe}/\text{H}] \approx -2.3$, i.e. similar metallicity as HD 84937), both to review survival of protostellar ${}^6\text{Li}$ and to determine how much mass (M_c) is to be enriched with spallated ${}^6\text{Li}$. We note that these models were able to reproduce the general morphology of the ${}^7\text{Li}$ observations (depleted cool dwarfs, plateau, and diluted subgiants).

2.1 Brief Review of Protostellar ${}^6\text{Li}$ Evolution

We will need to distinguish between protostellar ${}^6\text{Li}$ and surface spallated ${}^6\text{Li}$, so we briefly review the possible survival of protostellar ${}^6\text{Li}$ in present stellar atmospheres. Both Li isotopes can be destroyed (${}^6\text{Li}$ more easily) by (p, α) reactions at the base of the SCZ, more efficiently in deeper convection zones that are hotter at their base. Figure 2 shows the evolution of the mass M_c contained in the SCZ for model sequences of different

stellar mass, as a function of age (for $\alpha = 1.5$; Deliyannis and Demarque (1991) show the corresponding curves for the temperature and density at the base of the SCZ; see Deliyannis (1990) for a larger parameter space). The models begin their evolution fully convective, high up the Hayashi track; subsequently, the SCZ steadily becomes shallower until the turnoff (except in the final approach to the ZAMS), and then steadily becomes deeper during subgiant evolution (see DDK for further details). Most of the Li destruction occurs during the pre-main sequence, when the convection zones are deepest, and for the lowest mass models (which have the deepest convection zones). Figure 3 shows evolution of the same model sequences in the $M_c - T_{\text{eff}}$ plane. Lower mass models arrive on the ZAMS (diamond symbols) at lower T_{eff} , and preserve their rank as they evolve on the main sequence. For these reasons, the amount of protostellar ${}^6\text{Li}$ that survives today in dwarfs decreases with decreasing T_{eff} (Figure 4a).

Since it is difficult to distinguish observationally between field subgiants and dwarfs near the turnoff, such as in the case of HD 84937, we also consider subgiant evolution. Furthermore, it will turn out that slightly more evolved subgiants can provide a good test to distinguish between surface spallated ${}^6\text{Li}$ and protostellar ${}^6\text{Li}$. On an isochrone, subgiants have evolved from turnoff T_{eff} just beyond (hotter than) the present turnoff, and as such had preserved more protostellar ${}^6\text{Li}$ (and ${}^7\text{Li}$) than current dwarfs (that are cooler than the isochrone turnoff T_{eff}). After a model evolves past the turnoff, its SCZ begins to deepen (Figure 3). The ${}^6\text{Li}$ abundance remains constant until the SCZ deepens beyond the depth where protostellar ${}^6\text{Li}$ was preserved on the main sequence; subsequently, the surface ${}^6\text{Li}$ abundance will begin to dilute (Figure 3; for details see Deliyannis *et al.* 1990 and Ryan and Deliyannis 1994). Figure 4a summarizes the predicted ${}^6\text{Li}$ abundance surviving from a constant protostellar ${}^6\text{Li}$ abundance for both dwarfs and subgiants. The subgiant ${}^7\text{Li}/{}^6\text{Li}$ has been normalized to 20 at 6250 K, to agree with HD 84937. If protostellar Li has a primordial component plus roughly equal contributions of ${}^6\text{Li}$ and ${}^7\text{Li}$ produced by GCR's interacting with the ISM, and if the observed ${}^7\text{Li}$ abundance in HD 84937 is $A({}^7\text{Li}) = 12 + \log(n({}^7\text{Li})/n(\text{H})) \approx 2.1$, then this normalization is possible (with the models shown) if $\text{Li}_p \approx 2.0$ and ${}^7\text{Li}(\text{GCR}) \approx {}^6\text{Li}(\text{GCR}) \approx 1.5$. We note that the results shown in Figure 4a depend on age, metallicity, and other parameters (see DDK).

2.2. Surface Spallated ${}^6\text{Li}$: Dependence of M_c on T_{eff} (Mass and Age)

A similar figure (4b) will be presented in section 3 showing how surface spallated ${}^6\text{Li}$ varies as a function of T_{eff} for both dwarfs and subgiants, to be compared to Figure 4a. Here, we evaluate how the mass M_c , to be enriched with surface spallated ${}^6\text{Li}$ in section 3, varies with T_{eff} . Consider first the dwarf models. Figure 2 shows that at a given age, M_c is a steep function of stellar mass: for example, at 15 Gyr, in going from 0.65 to $0.75M_{\odot}$, the convection zone becomes more than two orders of magnitude shallower. M_c is also clearly a steep function of age: for example, in evolving from the ZAMS to 20 Gyr, the $0.70M_{\odot}$ model's SCZ becomes shallower by two orders of magnitude, with much of this decline occurring in late stages. In particular, from 15 to 20 Gyr the SCZ becomes shallower by one order of magnitude. The dependence of M_c on age implies that, unless surface spallation rates were much higher in the past, any observable surface spallated ${}^6\text{Li}$ is more likely to have been created recently. Since ${}^6\text{Li}$ is destroyed only during the pre-main sequence, it is important to note that (recently created) spallated ${}^6\text{Li}$ will indeed survive to the present.

Fortunately, the dependence of M_c on T_{eff} and age are related, and a great simplification occurs in the $T_{\text{eff}} - M_c$ plane (Figure 3). After models arrive on the ZAMS, they evolve *almost exactly* along the curve defined by the ZAMS itself (curve connected by diamonds in Figure 3); therefore, the dwarf M_c vs. T_{eff} curve is nearly independent of age (M_c isochrones fall nearly on top of each other). We will refer to this curve as the " M_c evolution pathway". Isochrones do diverge slightly with larger T_{eff} , but even at $T_{\text{eff}} = 6400$ K, 14.5 and 18 Gyr dwarf isochrones differ by only 0.1 dex. This suggests that we require neither a star's mass nor its age (both difficult to obtain) to estimate its M_c , though we do need to know its T_{eff} (less difficult to obtain). Given the likelihood that there is an age spread among globular clusters (Searle and Zinn 1978; Lee *et al.* 1990; Demarque *et al.* 1991; Sarajedini and Demarque 1991; Vandenberg *et al.* 1991; Chaboyer *et al.* 1992) as well in field halo stars (e.g. SN3), the near independence of M_c with age in the $T_{\text{eff}} - M_c$ plane is quite fortuitous.

M_c does remain a steep function of T_{eff} : in going from $T_{\text{eff}} = 6040$ K to 6620 K (for $\alpha = 1.5$) the convection zone becomes two orders of magnitude shallower. This implies that, for spallation rates independent of T_{eff} , the spallated ${}^6\text{Li}$ abundance will increase with T_{eff} (section 3). This trend is, unfortunately, similar to that expected for survival of protostellar ${}^6\text{Li}$ (section 2.1), and so does not allow us to distinguish easily between spallated and protostellar ${}^6\text{Li}$. However, the subgiants potentially can.

Consider now subgiants. Subgiant evolution of M_c is shown for $0.725M_\odot$ and $0.775M_\odot$ models in Figures 2 and 3; these correspond to approximate ages of 15 and 19 Gyr. The evolutionary timescale has shortened considerably, requiring less than one Gyr to go from $T_{\text{eff}} = 6500$ K to 5500 K, and the SCZ deepens significantly (and rapidly, see the nearly vertical tracks for $0.775M_\odot$ and $0.725M_\odot$ in Figure 2). Thus, unless spallation production rates increase proportionately (and quite significantly), ${}^6\text{Li}$ that was created by surface spallation during the (late) main sequence will now dilute. This is in *sharp* contrast to subgiant evolution protostellar ${}^6\text{Li}$. Whereas spallated ${}^6\text{Li}$ will dilute as the model evolves *immediately* past the turnoff, since the only region of the star containing ${}^6\text{Li}$ is essentially the convection zone itself, protostellar ${}^6\text{Li}$ will begin diluting only after the convection zone deepens past the entire (protostellar) ${}^6\text{Li}$ preservation region, which is orders of magnitude larger than what M_c is at turnoff (compare Figs. 4a and 4b). This is the key test we propose to discriminate between spallated and protostellar ${}^6\text{Li}$.

Because of the potential significance of this test, we point out evidence supporting the proposed depth of the Li preservation region. The numerous observations of ${}^7\text{Li}$ in halo subgiants of Pilachowski *et al.* (1993) follow closely the morphology of the standard DDK dilution tracks down to about 5000 K: the (subgiant) ${}^7\text{Li}$ plateau, the onset of subgiant ${}^7\text{Li}$ dilution, its progression, and its termination onto the diluted plateau (see Ryan and Deliyannis 1994). This suggests that the *profile* of the Li preservation region in stars may not be too different from that in the DDK models. However, we must point out that we are not advocating that the standard DDK models uniquely portray the true Li evolution in halo stars, since other models with additional physics (e.g. rotational mixing) might also have realistic ${}^7\text{Li}$ profiles (and thus also be consistent with the data), but have different implications for protostellar Li. (Indeed, the decline of subgiant Li below 5000 K is inconsistent with standard models, as is the decrease in the ${}^{12}\text{C}/{}^{13}\text{C}$ there, e.g. Deliyannis *et al.* 1994.) The point is that these subgiant data corroborate the predicted Li profile, and thus the depth to which protostellar ${}^7\text{Li}$ is preserved, which is a much deeper region than that contained in M_c at turnoff. Since both the temperature and density at the base of the SCZ are still much too low to allow burning of ${}^6\text{Li}$ near that phase (and are not likely to be sufficiently high to do so even in view of the model uncertainties), it is likely that protostellar ${}^6\text{Li}$ is also preserved to near its model depth, i.e. about twice as shallow as for ${}^7\text{Li}$, but still far deeper than the depth of SCZ near turnoff. Therefore, if ${}^6\text{Li}$ is observed in subgiants near the turnoff, protostellar ${}^6\text{Li}$ should also be observed with similar abundance near the onset of subgiant ${}^6\text{Li}$ dilution at 5800 K, whereas surface spallated ${}^6\text{Li}$ will have already diluted by one or more orders magnitude near 5800 K.

Finally, we point out an interesting difference between dwarf and subgiant M_c isochrones: at a given T_{eff} , the subgiant SCZ is shallower than the dwarf SCZ (e.g. Figure 3), so that for spallation rates independent of T_{eff} , subgiants will have more spallated ${}^6\text{Li}$ than dwarfs at the same T_{eff} . (This is also what is expected for protostellar ${}^6\text{Li}$.)

2.3. The Case of HD 84937

Literature estimates for the effective temperature of HD 84937 lie near 6250 K, with a range from 6100 K to 6400 K. If HD 84937 is a dwarf, this corresponds to $M_c = 1 \times 10^{-3} M_\odot$, with a range 3×10^{-3} to $3 \times 10^{-4} M_\odot$ (using $\alpha = 1.5$); if HD 84937 is a subgiant, it corresponds to $\sim 3 \times 10^{-4} M_\odot$ with a range of $\sim 7 \times 10^{-5} - 1 \times 10^{-3} M_\odot$, i.e. a factor of $3 - 4$ smaller. These are our best ranges for the star, with uncertainty (from all sources) perhaps of at least an order of magnitude. To be viable, surface spallation must be able to create an observable ${}^6\text{Li}$ abundance in at least this much mass.

3. NUCLEAR SPALLATION BY STELLAR FLARES

Production of the light isotopes by stellar flares has been previously investigated by several groups (eg. Ryter *et al.* 1970; Canal *et al.* 1975; Walker *et al.* 1985). The main aim of these previous studies was to establish if such a mechanism could be a credible alternative to the GCR hypothesis for the universal origin of the light isotopes. The general consensus from these studies was that flare production (at least as the sole mechanism) was not a viable option.

However, in this work our aim is not as grandiose. Given the importance of the SLN observation, we simply wish to determine the feasibility of flare production of ${}^6\text{Li}$ in HD 84937 – and more importantly to determine observational tests which would allow such flare production to be discriminated against. For it is only if flare induced ${}^6\text{Li}$ can be safely disregarded in such stars would it then be reasonable to draw any cosmological implication from the observational data.

Let us first consider the energetics of ${}^6\text{Li}$ production in HD 84937. For the stellar flare we adopt a source spectrum of the form

$$\Phi_i(E) = \alpha_i E^{-\gamma} \quad i = \text{p}, \alpha, \quad (3.1)$$

where α_i is a normalization constant, E is the energy per nucleon, and the spectral index γ is taken to be in the regime 2 – 7. Due to energy losses, however, the source spectrum can evolve as the particles are transported through matter. In terms of Π , the amount of matter traversed in atoms cm^{-2} , such evolution of the spectra can be approximated as

$$\Phi_i(E, \Pi) = \frac{\alpha_i E_i}{(E_i^2 + 2A_i \Pi)^{\frac{\gamma+1}{2}}}, \quad (3.2)$$

where $A_i = 2Z_i^2 \times 10^{-21} \text{ MeV}^2 \text{atom}^{-1} \text{ cm}^2$ (Z being the nuclear charge). Clearly, in the limit $\Pi \ll E^2/2A$, the transported spectra collapses to the original source spectra. As discussed in Ryter *et al.* (1970), one can make various approximations in order to estimate, η , the energy required to form one atom. These various approximations depend on the ionization level of the medium through which the flux propagates, and whether the particles are re-accelerated after leaving the source. For example, assuming no re-acceleration in a neutral plasma, the energy required to form one light isotope from a flux $\Phi_i(E)$ impinging on particles j can be written as

$$\eta = \frac{\int_0^\infty \Phi_i(E) E dE}{\int_0^\infty \left[\Phi_i(E) \sum_j \frac{n_j}{n_H} \int_{Q_j}^E \frac{\sigma(E')}{\epsilon(E')} dE' \right] dE}, \quad (3.3)$$

where n is number density (H refers to hydrogen), $\sigma(E)$ is the production cross section (listed by Read and Viola 1984), Q_j the corresponding energy threshold, and $\epsilon(E) = (1/n_H)(dE/dx)$ is the stopping power of the gas (x being the length of the particle path). Tabulations of the stopping power in neutral matter can be found in Barkas and Berger (1964), whereas the stopping power in plasmas are discussed in detail by Spitzer (1965). For typical flare parameters, equations (3.2) and (3.3) give $\eta \sim 1$ erg.

Of course, as already indicated, the actual values of η depend on the approximation made, and the input flare parameters. The low energy cut-off in the flux spectra also plays an important role. With variation of these parameters, and allowance for the presence of re-acceleration and non-zero ionization levels, η is typically found to lie in the range 1 – 1000 ergs (Ryter *et al.* 1970; Canal *et al.* 1975; Canal *et al.* 1980). The lower values of η are usually associated with hard (lower γ) flares in hot environments.

Adopting the stellar model parameters discussed in section 2, we can estimate the total energy, E_T , required for production of all the ${}^6\text{Li}$ detected in HD 84937. For example, assuming $\eta = 1$ erg and a convective envelope mass $M_c \sim 10^{-3} M_\odot$, we find $E_T \sim 10^{42}$ ergs. We can put this value of E_T in perspective. Assuming a production timescale of 10^9 years, the “average” required luminosity of a flare would be 1 part in 10^6 – in terms of HD 84937’s luminosity. Another way of putting this is to consider the flare activity required. Large solar flares typically

provide 10^{32} ergs. Given the evolutionary timescales, the number of such flares required would be ~ 10 per year for $E_T = 10^{42}$ ergs. However, it is worth noting that given the uncertainty in the convective envelope mass, the required flare activity could be as low as one 10^{32} erg flare per 100 years.

Given that the required energy requirements can at least in principle be fulfilled, as a working hypothesis let us assume flare induced proton and alpha-particle interactions with ambient alpha-particles and CNO nuclei in the stellar atmosphere are the main source of the ${}^6\text{Li}$ observed in HD 84937. We now calculate the light isotopic ratios in HD 84937 based on this premise.

The number density n_k ($k = {}^6\text{Li}, {}^7\text{Li}, {}^9\text{Be}, {}^{10}\text{B}, {}^{11}\text{B}$) of each isotope produced by a flux of i particles can be described by the differential equation

$$\frac{dn_k}{dt} = \sum_j \left[\int_{Q_j}^{\infty} \Phi_i(E, \Pi) \sigma(E) S_k(E) dE \right] n_j(t) \quad . \quad (3.4)$$

The parameter $S_k(E)$ represents the survival probability of the particle k produced. Adopting Fe and CNO abundances representative of HD 84937, namely, $[\text{Fe}/\text{H}] = -2.3$, $[\text{O}/\text{Fe}] = 0.5$, $[\text{C}/\text{Fe}] = [\text{N}/\text{Fe}] = 0$, and adopting $\alpha_p/\alpha_\alpha = 10$, we solve equation (3.4) for a variety of flux spectra. The calculated abundances are then convolved with the stellar models discussed in section 2. This then gives predictions of the isotopic abundances in the stellar atmosphere as a function of T_{eff} . On the subgiant branch, the calculated number densities, $n({}^6\text{Li})$ and $n({}^7\text{Li})$, are again normalized by setting $n({}^6\text{Li}) = n_o({}^6\text{Li})$ at $T_{eff} = 6250\text{K}$ – the observed values being $n_o({}^6\text{Li}) = 6.6 \times 10^{-12} n_H$ and $n_o({}^7\text{Li}) = 132 \times 10^{-12} n_H$ (SLN). The primordial ${}^7\text{Li}$ value is then set at $n_p({}^7\text{Li}) = n_o({}^7\text{Li}) - 20Rn({}^7\text{Li})$, R being the calculated ${}^7\text{Li}/{}^6\text{Li}$ ratio. It should be noted that this pre-spallation value may be different from the protostellar value due to stellar processing (see section 4), though in the case of standard models near the turnoff the two would be almost identical.

3.1. Subgiants

The two main parameters in our calculations are the spectral index γ and the grammage Π . For the purpose of calculation let us assume the values $\gamma = 3$ and $\Pi = 0.1 \text{ g cm}^{-2}$. We also assume that the flare activity remains constant. Figure 4b shows the calculated ${}^7\text{Li}/{}^6\text{Li}$ ratio as a function of T_{eff} for a star which is in the subgiant phase of evolution. It can be clearly seen that closer to the turn-off point (i.e. higher T_{eff}) the ${}^7\text{Li}/{}^6\text{Li}$ becomes significantly smaller, reaching values as low as ~ 5 . Contrary to this, we can see that far from the turn-off point the ${}^7\text{Li}/{}^6\text{Li}$ ratio becomes larger, rapidly increasing beyond values of 30 for T_{eff} 's cooler than about 6200K . The important point is, however, that as discussed in section 2.1, if the lithium isotopes have a protostellar origin then the ${}^7\text{Li}/{}^6\text{Li}$ ratio (~ 20) should remain a constant in this T_{eff} region.

This difference in predictions, namely constant ${}^7\text{Li}/{}^6\text{Li}$ toward cooler T_{eff} (protostellar ${}^6\text{Li}$) versus increasing ${}^7\text{Li}/{}^6\text{Li}$ toward cooler T_{eff} (spallated ${}^6\text{Li}$) is large enough to be observable by current techniques, and represents our key discriminatory test between flare and protostellar production. We note that the test is robust in the sense that different input parameters for the flux spectra (i.e. different values of γ and Π) give very similar results to those shown in Figure 4b. The predicted trend (and size of the effect) of the flare production scenario is independent of the input parameters. This is essentially because, to first order, the controlling effect is the size of the convective envelope at a given T_{eff} .

Variations in the flare activity with time and from star to star, can obviously affect the calculated yield. This would result in a less uniform increase of the predicted ${}^7\text{Li}/{}^6\text{Li}$ ratio as a function of T_{eff} . That is, there may be differences (a spread) in ${}^6\text{Li}$ abundances at a given T_{eff} . Similarly, the likelihood of an age spread in the Galactic halo (even at constant metallicity) suggests that stars could form with different initial (GCR produced) protostellar ${}^6\text{Li}$, again resulting in a spread of ${}^6\text{Li}$ at a given T_{eff} . Nonetheless, the observational test would remain in an average sense – in a sufficiently large sample. Constancy (on average) of the observed ${}^7\text{Li}/{}^6\text{Li}$ ratio with T_{eff} on the subgiant branch would support a protostellar origin, whereas increase of the same ratio (on average) at cooler T_{eff} would support flare production.

3.2. Dwarfs

A similar calculation could be carried out for the dwarf case. However, here our ignorance of the flare parameters will play a more important role. The reasons for this is that the predicted trend of the ${}^7\text{Li}/{}^6\text{Li}$ ratio is similar for both the flare and the protostellar origins above $T_{\text{eff}} = 5800$; compare fig 4a and b. This can be seen from the discussions of section 2.1, where it is discussed why protostellar ${}^7\text{Li}/{}^6\text{Li}$ ratio will increase with decreasing T_{eff} for dwarfs. However, since the mass of the convective envelope increases with decreasing T_{eff} for dwarfs, the predicted ${}^7\text{Li}/{}^6\text{Li}$ ratio from flare production will likewise increase with decreasing T_{eff} . As the trend of the ${}^7\text{Li}/{}^6\text{Li}$ ratio with T_{eff} is then similar for both production mechanisms, any discriminatory test would rely solely upon the amount of flare production versus the amount of lithium destruction on the pre-main sequence. Clearly, this would require detailed knowledge of the flare history over the lifetime of the star – knowledge of which eludes us. There are also model uncertainties in evaluating the precise amount of pre-main sequence ${}^6\text{Li}$ destruction (DDK), further confounding attempts to discriminate between scenarios using the dwarfs.

We see therefore, that unlike subgiants, dwarfs are not a good testbed of the differing production scenarios. Only if large ${}^7\text{Li}/{}^6\text{Li}$ ratios are observed in dwarfs, and are deemed incompatible with the calculated pre-main sequence depletion factors, could indirect evidence for some non protostellar origin be forthcoming.

For cooler dwarfs ($T_{\text{eff}} < 5800\text{K}$), a ${}^6\text{Li}$ detection would point to a spallative origin since protostellar ${}^6\text{Li}$ would have been completely destroyed. However, though ${}^7\text{Li}/{}^6\text{Li}$ is much smaller than the protostellar case, at a value > 100 it may be too large to allow detection of spallative ${}^6\text{Li}$.

3.3. B/Be ratios

Although the ${}^7\text{Li}/{}^6\text{Li}$ ratios predicted above are largely independent of the flare parameters γ and Π , this is certainly not the case for the predicted Beryllium and Boron yields. That is, the predicted Li/Be and Li/B ratios can vary widely, dependent on the input values of γ and Π . In addition, these latter ratios are dependent on the assumed ratio of alpha-particle to proton ratio in the flare spectra (since the lithium isotopes are mainly produced by $\alpha-\alpha$ fusion reactions at low metallicity). For practical purposes this translates into the fact that the flare mechanism has little predictive power with regard to Li/Be and Li/B ratios. Although the recent detection of Be in HD 84937 by Boesgaard and King (1993) can be accounted for by flare production, in general the Li/Be ratio predicted solely from flares can be very large. In such circumstances, additional production of Be and B from some other mechanism (eg GCR's) would be necessary. Although B has recently been detected in a few metal-poor halo stars (Duncan *et al.* 1992; Edvardsson *et al.* 1994), as yet there has been no detection of B in HD 84937.

However, the tight predictive power of GCR spallation theory, does allow for discriminatory tests to be made. This is better described in terms of the B/Be ratio, as this ratio is more independent of the alpha-particle to proton flux in the flare, and is free of the issues surrounding the primordial lithium value. Our calculations show the B/Be ratio predicted by a flare mechanism can readily reach values of ~ 100 for typical spectra. Such an increase in the B/Be ratio with γ is well known (eg. Walker *et al.* 1985), and can be understood from considerations of the energy dependence of the spallation cross section data. Simply put, spectra with large γ 's give more weight to the low energy regime where the lower threshold of the B production reactions lead to larger B/Be ratios. A more detailed discussion of the energy dependence of B/Be is given by Duncan *et al.* (1992).

The B/Be ratio predicted by GCR spallation theory, on the otherhand, is constrained to be less than 20 (somewhat higher values are possible but only at the expense of adopting contrived GCR spectra). This upper limit of 20 arises from the folding of the cross-section data and input initial abundances, with the present-day observed cosmic-ray spectrum. Although this measured spectrum could have evolved from an initially different spectrum prevalent in the early galaxy (Prantzos *et al.* 1993), nuclear destruction effects limit such evolution, and the predicted B/Be ratio in the early galaxy is essentially the same as that predicted using the present day cosmic-ray spectrum (Malaney and Butler 1993). We note, however, that Deliyannis and Pinsonneault (1990) suggest that rotational stellar models may allow for slight Be (but no B) depletion, thereby increasing the B/Be ratio inferred from observation by 1.5. Also, we note the work of Kiselman (1993), who cautions that non-LTE

effects can substantially raise the value of B/Be inferred from observations of metal-poor stars. However, in their non-LTE analysis of HD 140283, Edvardsson *et al.* (1994) conclude that the B abundance should be increased by ~ 0.5 dex relative to the LTE value, resulting in a B/Be range of 9 – 34 and therefore still consistent with a GCR origin. Only if it can be established from observation that B/Be > 20 (> 30 if rotational stellar models are employed) in a halo star atmosphere, would there then be a strong case for some production mechanism other than GCR spallation.

We caution here that neutrino-spallation processes may confuse the issue. Neutrino-spallation can lead to production of B (Woosley *et al.* 1990), and perhaps also to small yields of Be (Malaney 1992). The predicted B/Be ratios from neutrino-spallation acting alone are typically very large (> 200). Recently, Olive *et al.* (1994) have argued that GCR plus neutrino spallation leads to a relatively model independent prediction of B/Be > 50 for $[\text{Fe}/\text{H}] < -3$. In view of this, B/Be > 30 at higher metallicities ($[\text{Fe}/\text{H}] \sim -2$) would be the key indicator of some flare-induced light isotope production.

4. DISCUSSION

So far we have presented a simplified picture of how flares might be able to produce observable amounts of ^6Li in turnoff halo stars, and how one might be able to distinguish between surface spallated ^6Li and protostellar ^6Li . In this section we discuss how this picture might be affected by various complications.

4.1. Dependence of M_c on Metallicity

It is hoped that ^6Li observations will be attempted in a large sample of halo dwarfs with a wide variety of metallicities. It is therefore relevant to examine how our results might depend on metallicity. The models of DDK show that both destruction of protostellar ^6Li and also subgiant evolution of protostellar ^6Li are only slightly dependent on metallicity. Fortunately, M_c also depends only weakly on model metallicity for halo metallicities, with the M_c evolution pathway for $Z = 10^{-3}$ lying at most 0.2 dex above the $Z = 10^{-4}$ pathway at their widest point of separation, which is unimportant for our purposes here (Figure 5). The M_c evolution pathway for $Z = 10^{-5}$ nearly coincides with that for $Z = 10^{-4}$. Note that $Z = 10^{-3}$ models have lower turnoff T_{eff} 's than $Z = 10^{-4}$ models of the same mass (turnoff age). For subgiants, the dependence of M_c on metallicity is more significant: at 6300 K, M_c differs by a factor of roughly 3 between $Z = 10^{-3}$ and $Z = 10^{-4}$, though the difference effectively disappears at lower T_{eff} . On the other hand, fortuitously, the uncertainty in M_c due to ambiguity in evolutionary status is smaller for model subgiants with $Z = 10^{-3}$ than with $Z = 10^{-4}$.

4.2. Dependence of M_c on the Choice of Mixing Length

Figure 6 shows that near the turnoff, M_c depends strongly on the choice of mixing length: in going from $\alpha = 1.5$ to 1.1 at a T_{eff} (at 17 Gyr), the SCZ becomes an order of magnitude shallower. Unfortunately, choice of appropriate value of α is fraught with uncertainty. One possible method is to take advantage of the sensitivity of α to model radius and the fact that the solar radius is known precisely. This yields $\alpha = 1.4$ for a solar model with the same treatment of physics as in the models of DDK (but there is nothing sacred about this value: models that treat input physics or even convection differently may require a different value for α). However, there is no guarantee that this value, even if appropriate for the sun, will be appropriate for halo dwarfs. In fact, reasons have been discussed as to why other values may be more appropriate for halo dwarfs (Deliyannis and Demarque 1991; Chaboyer *et al.* 1992). It should be borne in mind also that mixing length (convection) theory does have its limitations, and that the effective mixing length could well be a function of stellar mass, age, and other variables. In short, even if we knew a star's T_{eff} perfectly, there is still great systematic uncertainty in (absolute) M_c due to uncertainty in the treatment of convection. However, even if convection can currently only be modelled approximately, convection itself may be rather similar in metal poor stars of similar T_{eff} , so the models may be giving us a better estimate of the differences in M_c between stars.

4.3. Sensitivity to Model Physics

Deliyannis and Demarque (1991) caution that M_c depends sensitively on opacities and the treatment of other input physics, so a comparison to other models might provide a useful indicator as to the size of the model

uncertainties in M_c . For example, the models of Proffitt and Michaud (1991, PM) do treat some of the input physics a bit differently (for discussion see Chaboyer *et al.* 1992; Proffitt and Vandenberg 1991). Nevertheless, the standard dwarf M_c isochrone that PM show, at 15 Gyr, $[\text{Fe}/\text{H}] = -2.3$, and $\alpha = 1.5$, is nearly identical to our corresponding M_c evolution pathway (for $[\text{Fe}/\text{H}] = -2.3$, $\alpha = 1.5$). However encouraging, the comparison is not so straightforward; for example, PM's value of $\alpha = 1.5$ is not solar calibrated (Proffitt 1994), and there are some unavoidable differences in the input parameters as well. Nonetheless, it is not unreasonable to assume that the model uncertainties in M_c are closer to of order a factor of two or so, rather than an order of magnitude; this accuracy suffices for the purposes of this paper. Support for this comes by comparing to the models of Chaboyer (1994), which have made use of some improvements in the input physics (e.g. opacities). The new M_c 's are indeed within a factor of 2-3.

4.4. Additional physics: diffusion

The possibility that microscopic diffusion (e.g. gravitational settling, thermal diffusion) has affected surface Li abundances in halo stars has been discussed and debated (Michaud *et al.* 1984, Deliyannis *et al.* 1990, Chaboyer *et al.* 1992). Diffusion of ^6Li should be quite similar to that for ^7Li . It has been argued that the ^7Li abundances observationally constrain the effects of diffusion (acting alone) to be rather small (Deliyannis and Demarque 1991). Conceivably, diffusion can be more important if its effects are masked by rotational mixing (^7Li then no longer tracks diffusion, since it can be mixed and destroyed); but in that case, the effects of rotational mixing are even more important (below). In either case, diffusion does not significantly alter our results.

4.5. Additional Physics: rotational mixing

Recall that the predictions of standard stellar models are blatantly contradicted by Pop I data (e.g. the Boesgaard Li gap and depletion of Be in F stars, the degree and timing of Li depletion in open clusters, the dispersion of Li abundances observed in open clusters, the higher Li abundances seen in short period tidally locked binaries). In contrast, rotational models do a much better job of explaining these (and other) observations. One must therefore consider the possibility that rotational mixing has been important for Pop II stars as well, especially since rotational models are able to explain more features of the Pop II observations than do standard models. The possibility that rotationally induced mixing has affected the Li isotopes introduces complications. The most obvious of such complications would be a likely inconsistency with standard BBN; since if significant Li depletion has taken place in the halo stars, the value of Li_p would be above that predicted by standard BBN. The recent quasar D observation (if taken at face value) also suggests an inconsistency in standard BBN, but rotational mixing could conceivably solve both problems through its effect on ^3He on the giant branch, and the resulting modifications to the $\text{D}+^3\text{He}$ arguments (Deliyannis *et al.* 1994).

In the context of these rotational depletion models, one explanation for the origin of any detected ^6Li in halo stars would be surface spallation – rather than protostellar. This would seem reasonable since one anticipates the rotationally-induced depletion factors for ^6Li to be larger than those for ^7Li , and if initially the protostellar ^6Li was much less than protostellar ^7Li , then very little ^6Li would still be present in the stellar atmosphere.

Of course, an alternative solution could be that *both* the protostellar ^6Li and ^7Li were initially higher than currently observed, and that the preferential destruction of ^6Li relative to ^7Li results in the $^7\text{Li}/^6\text{Li}$ ratio now observed in HD 84937. The main point is that rotational depletion (which is a very different process from nuclear burning at a given temperature) is more analogous to a dilution process, where Li rich material from above is mixed *slowly* with Li poor material from below. Thus, rotational depletion of ^6Li need be only slightly larger than that for ^7Li , depending on the rotational parameters and M_c relative to the sizes of each Li preservation region. ^6Li does depend more strongly on the rotational parameters than does ^7Li . So, for example, for an initial angular momentum J_o just slightly smaller than case J0 shown in DDK, ^7Li depletion may be a factor of 7 - 8 and ^6Li depletion only a factor of 25 - 40. This would be consistent with $A(\text{Li}_p) \approx 2.9$, $^7\text{Li}(\text{GCR}) \approx ^6\text{Li}(\text{GCR}) \approx 2.2$, giving current observed abundances of $^7\text{Li} \approx 2.1$ in HD 84937 and ^6Li a factor of 20 smaller, consistent with SLN. Only slightly higher J_o would affect ^7Li very little but push ^6Li down to unobservable levels, whereas only slightly lower J_o could result in even lower $^7\text{Li}/^6\text{Li}$ ratios.

Further discussions of this point, and issues as to whether high ${}^6\text{Li}$ (GCR) values are feasible within the context of GCR models, are beyond the scope of the present work. Suffice to say that GCR models cannot readily reproduce the shallow slope of the observed Be-Fe relation (eg. see discussion in Malaney and Butler 1993), and the introduction of more complex GCR models may open up new possibilities for interpreting ${}^6\text{Li}$ detections in halo stars in the context of rotational depletion. One could readily *contrive* a new GCR model which predicts high ${}^6\text{Li}$ (GCR), while remaining consistent with all the available light isotope data at low metallicities.

Finally, we wish to point out that, in the presence of rotationally-induced depletion, our proposed test for distinguishing between the different production scenarios is largely negated. Depletion of both protostellar and spallated ${}^6\text{Li}$ would continue to the present, though would be at its weakest in the last several Gyr. Since protostellar ${}^6\text{Li}$ depletion is larger than that of ${}^7\text{Li}$, it is possible that ${}^6\text{Li}$ would be preferentially depleted on the subgiant branch, perhaps increasing ${}^7\text{Li}/{}^6\text{Li}$ by a factor of two or so there. This lessens the difference between the subgiant spallated ${}^6\text{Li}$ vs. protostellar ${}^6\text{Li}$ cases discussed above. Furthermore, since protostellar ${}^6\text{Li}$ depletion is more sensitive to rotational parameters, such as J_o , than is ${}^7\text{Li}$, rotational models would predict a large variety of ${}^7\text{Li}/{}^6\text{Li}$ in subgiants, with ${}^6\text{Li}$ possibly detectable in some but not in others. Unfortunately, these factors make it more difficult to distinguish between alternative scenarios.

Detections of ${}^6\text{Li}$ in halo dwarfs (assuming they could be demonstrated to be protostellar and NOT spallative in origin) could, nonetheless, offer some useful constraints for rotational models. The level in HD 84937, for example, argues against models with higher initial angular momentum (and wind law and other parameters as assumed), such that ${}^7\text{Li}/{}^6\text{Li} > 100$. The higher the detected ${}^6\text{Li}$ abundance, the stronger the constraints, at least in those stars.

5. CONCLUSIONS

We have investigated in detail the possibility that flare activity on the surface of halo stars may lead to observable quantities of ${}^6\text{Li}$ – thereby impacting on the conclusions to be drawn from any observation of this isotope in a metal-poor atmosphere. Our calculations have been largely on the premise that standard BBN is an accurate description of primordial isotope production, and that standard stellar evolution models are applicable. We found that energetic flares could account for the quantity of ${}^6\text{Li}$ observed in HD 84937, therefore limiting the reliability of cosmological implications drawn from this type of observation. As such, we proposed a future observational test which would allow a discrimination against flare production to be made.

A critical quantity in our calculations was the mass of the surface convective zone, M_c . We found that on an isochrone, M_c decreases steeply with increasing T_{eff} , decreases steeply with age, and was only weakly dependent on metallicity. M_c deepens rapidly on the subgiant branch, but for lower metallicities remains a bit shallower than M_c in dwarfs of the same T_{eff} . Assuming surface spallation production rates are approximately independent of time and T_{eff} , flare-spallated ${}^6\text{Li}$ is most likely to be observed in the hottest, oldest dwarfs, and preferentially in subgiants. More evolved subgiants will have diluted their flare-spallated ${}^6\text{Li}$, but will have preserved their protostellar ${}^6\text{Li}$. Given a statistically meaningful sample of observations of the ${}^7\text{Li}/{}^6\text{Li}$ ratio in metal-poor halo stars, contamination by flare production could be discriminated against, and important cosmological implications could be more safely inferred. If rotational Li depletion is applicable, then complications are introduced both in applying our test to distinguish between flare-spallated ${}^6\text{Li}$ and protostellar ${}^6\text{Li}$, and in general in interpreting the ${}^6\text{Li}$ abundances.

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FIGURE CAPTIONS

Figure 1: Color magnitude diagram of M92, with isochrones from Demarque, Deliyannis, and Sarajedini (1991) and data from Stetson and Harris (1988). Two possible positions for the evolutionary status of HD 84937 are shown, based on a B-V color of 0.40: dwarf (A) and subgiant (B).

Figure 2: Evolution of the mass M_c contained in the surface convection zone (SCZ) for $[\text{Fe}/\text{H}] = -2.3$ ($Z = 10^{-4}$) and $\alpha = 1.5$, for masses from 0.650 to $0.800M_\odot$ in steps of 0.025 (some masses labeled), as a function of age. X's mark the ZAMS. For clarity, pre-main sequence and subgiant evolution is shown for only a few model sequences.

Figure 3: Evolution of M_c in the $T_{\text{eff}} - M_c$ plane for $Z = 10^{-4}$ model sequences. Arrows indicate the direction of evolution. For clarity, pre-main sequence and post-turnoff evolution is shown for only a few model sequences. The ZAMS (shown in diamonds for each model stellar mass) also defines the main sequence M_c evolution pathway. After the ZAMS, concave down curves show main sequence evolution while concave up curves show subgiant evolution. The numbers indicate stellar mass in solar masses.

Figure 4a: Predicted evolution of protostellar ${}^7\text{Li}/{}^6\text{Li}$, at 17 Gyr (see text for parameters and normalization), showing the results of pre-main sequence Li destruction.

Figure 4b : Predicted trend of the ${}^7\text{Li}/{}^6\text{Li}$ ratio from flare activity as a function of T_{eff} for both the subgiant and the dwarf phases of evolution.

Figure 5: Comparison of dwarf isochrones (concave down) and subgiant evolutionary tracks (concave up) of different metallicities ($Z = 10^{-4}$, 18 Gyr; $Z = 10^{-3}$, 17 Gyr).

Figure 6: 17 Gyr dwarf isochrones for two different choices of mixing length, at $Z = 10^{-4}$.